Synthesis and Identification of Superheavy Elements in Reactions with ^{48}Ca Beams

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Experimental methods for the identification of newly synthesized heaviest isotopes of elements $Z = 112$ and 114 with the use of ^{48}Ca beams are discussed.

1. Introduction

For the identification of new nuclides undergoing α decay a method for the investigation of consistent α decays, the so-called α-α correlation analysis, has been employed since mid-60ties. This method is based on the fact that a decay chain starting from unknown isotopes should be ended in the known region of isotopes with the known decay properties.

Using the neutron-rich isotope ^{48}Ca as a bombarding beam for the synthesis of new heaviest nuclei we found ourselves in a completely unknown region where all decay chains were started and finished with isotopes having unknown decay properties. According to the calculations[1,2] the decay chains which started from the neutron-rich ($N = 171$–175) isotopes of elements 112–114 after a few α decays should be terminated by spontaneous fission in the region of elements 104–110. Taking into account the above mentioned problems we performed a number of experiments with the use of recoil separator VASSILISSA,[3] each experiment being the basis for the following one. For example, we investigated the complete fusion reactions $^{48}\mathrm{Ca} + ^{238}\mathrm{U} \rightarrow ^{286}112^*$ and $^{48}\mathrm{Ca} + ^{242}\mathrm{Pu} \rightarrow ^{290}114^*$ in which the targets differ by an α particle.[4,5] It means that the isotopes which can be produced in a subsequent experiment should decay into the isotopes which were obtained in the previous experiments. But for direct determination of Z of the detected nucleus it is necessary to have the mass resolution at the level of a few mass units (≈1%) so that one could distinguish between the xn and αxn deexcitation channels. It is obvious that to have a possibility of mass determination, i.e. to distinguish between the xn and $(x+1)n$ deexcitation channels, the necessary mass resolution should be better than 1 amu (0.3%).

2. Experimental Methods

2.1. Separator VASSILISSA. As a first step for improving the analysis and identification of complete fusion reaction products, a new dipole magnet, having a deflection angle of 37 degrees, has been installed behind the separator VASSILISSA, replacing the old 8° magnet.[5] In order to obtain sufficient position separation between nuclides with different masses a new detector system, having a focal plane 32 strip detector 60×120 mm^2 in size, has been also developed.

Test experiments with ^{40}Ar and ^{48}Ca beams and Dy, Yb, and Pb targets showed that the new magnet provided an additional suppression for unwanted products by the factor of about 10 and a possibility to have the mass resolution for heavy nuclei with masses of about 300 amu at the level of 2.5%.

Using a specific ion optical regime of the separator it was possible to see at the focal plane of the separator the charge distribution of scattered ^{40}Ar ions. These data were used for the calibration of TOF-Energy spectra together with the relation between the strip number (deflection angle) and $B\rho$ (magnetic rigidity) of ER's.

The time resolution of the separator time-of-flight system was about 0.7 ns, which corresponds to the value of about 1% (for slow evaporation residues). For each ER passing through the separator and detected at the focal plane, the time-of-flight (speed "v" of ER) and position of implantation/strip number (magnetic rigidity "$B\rho$" of ER) were measured.

It was possible to calculate the mass of the ER's, detected at the focal plane. For different charge states ($Q = 17$, 18, and 19) the result was $A = 198.1 \pm 1$, 197.8 ± 1, and 198.4 ± 1, respectively. Taking into account that the calculations were made for the isotope ^{197}Po, formed in the complete fusion reaction $^{164}\mathrm{Dy}(^{40}\mathrm{Ar}, 7n)^{197}\mathrm{Po}$, the obtained mass resolution could be estimated as about 2%.

In the case of the reaction $^{40}\mathrm{Ar} + ^{164}\mathrm{Dy} \rightarrow ^{204}\mathrm{Po}$ the cross section values reach hundreds of microbarns. For the reaction $^{40}\mathrm{Ar} + ^{208}\mathrm{Pb} \rightarrow ^{248}\mathrm{Fm}$ these values are equal to tens of nanobarns. Using the reaction $^{208}\mathrm{Pb}(^{40}\mathrm{Ar}, 2n)^{246}\mathrm{Fm}$ we estimated that the new dipole magnet provided an additional suppression factor of about 10 for scattered ions. Very clean α spectra were obtained. From the comparison with literature data[6] we could estimate that transmission efficiency for ^{246}Fm ER's was about 20%. The obtained mass resolution for ^{246}Fm ER's, calculated according to the measured TOF and strip number, ranged from 244.5 to 247.2 that corresponded to an accuracy of about 2.5%.

2.2. On-line Mass Spectrometer. The heaviest nuclei newly synthesized with the use of ^{48}Ca beams are in the unknown region where all decay chains are started and finished with isotopes having unknown decay properties. In this case for unambiguous identification of such nuclei it is necessary to perform direct mass determination with a resolution of better than 1 amu at the level of 300 amu. It becomes possible with specially designed experimental setups, one of the variants is on-line mass spectrometers guided with ion sources, the so-called ISOL systems. At the FLNR the project of such spectrometer is now being developed. Neutron-rich isotopes of elements with $Z = 112$ and 114 which have rather long half-lives will be implanted in a hot catcher. After that they will diffuse from the catcher into the volume of the ECR ion source. The atoms ionized in the ion source to the charge state +1 (with an efficiency close to 100%) will be accelerated with 30–40 kV and mass-separated. The mass resolution $M/\Delta M$ of about 1000 will be obtained for the nuclei in the mass region of about 300 amu. The name of this project is MASHA (Mass Analyzer of Super Heavy Atoms).

2.3. Chemical Investigations of SHE. The relatively long half-lives of the new isotopes with $Z = 112$ and 114, synthesized in reactions with ^{48}Ca ions, open new prospects for the investigation of the chemical properties of superheavy elements. The problem consists in finding out if these elements are homologues of Hg and Pb and how strong is the influence of relativistic effects in electron shells in superheavy atoms. Of course the investigation of chemical properties could help in the determination of the atomic number Z of the element but not the mass number, however it will still be a big progress, providing the experiments

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are successful.

The first attempt to identify chemically element 112 (E112) was made in January 2000. A 2 mg/cm^2, 20 mm in diameter ^{238}U(^{nat}U) target, containing 100 μg of ^{nat}Nd was prepared onto a 2 μm HAVAR foil, which also served as a vacuum window on a supporting Cu grate (its transparency was 62%). After a 10-day irradiation with ^{48}Ca ions (262 MeV, 0.2–0.4 pμA), an integral beam dose of 6.85×10^{17} was accumulated. The recoils were thermalized in pure helium at atmospheric pressure and transported through a 25 m long PTFE capillary to the detectors. The transportation time was 25 s at a gas flow rate of 500 cm^3/min. The detection apparatus consisted of 8 chambers connected in series. The PIPS detectors in chambers 1–6 were coated with Au, and in chambers 7 and 8 with Pd. The chambers were positioned inside an assemblage of 84 ^{3}He-filled detectors (in a moderator) to register prompt fission neutrons. If E112 behaved chemically like Hg and all the quantities measured for Hg were also valid for E112, we could expect the detection of some three SF events, taking into account the cross section value of about 5 pb. But no events with the characteristics described above were registered. Thus the experiment did not provide an unambiguous answer as to the physical and chemical properties of element 112, namely whether the chemical properties of E112 are more Rn-like, or the poor statistics resulted in a random value of zero. However, the experiment undoubtedly showed a possibility of chemical identification of SF nuclei produced with picobarn cross sections. At the next stage of this work it is planned to increase the beam dose at least twice and to upgrade the detector system: at the exit of the PIPS detector chambers the gas will pass through a special ionization chamber to measure α decays and SF events of nuclei remaining in the gas.

3. Conclusion

The experiments performed with ^{48}Ca beams are the first step in a long-term program aimed at the synthesis and study of decay properties of superheavy nuclei with neutron numbers close to the predicted spherical shell. The relatively long half-lives of the new isotopes with $Z = 112$ and 114 (even-odd and odd-odd isotopes which could be obtained in reactions with ^{237}Np and ^{243}Am targets could have even longer half-lives), synthesized in the reactions with ^{48}Ca ions, dictate the necessity of upgrading the existing experimental setups and developing new ones, thus providing the possibility of direct mass measurements with an accuracy of 1 amu, but on the other hand open new prospects for the investigation of chemical properties of superheavy elements.

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